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CONSTRUCTION PRODUCTIVITY ADVANCEMENT RESEARCH (CPAR) PROGRAM

EVALUATION OF NONDESTRUCTIVE METHODS FOR DETERMINING STRUCTURAL CONFIGURATIONS OF EXISTING BUILDINGS

by

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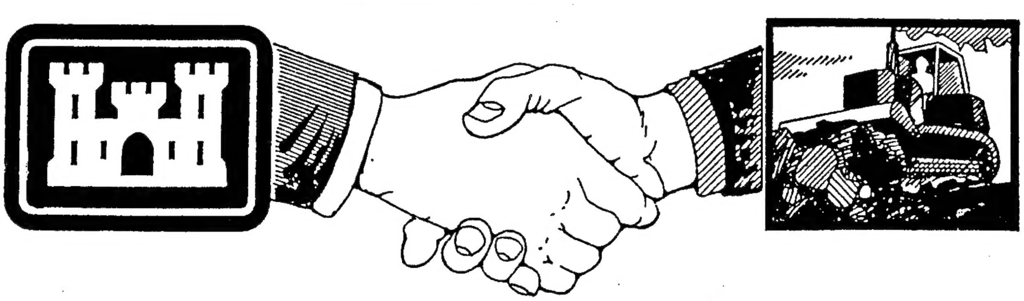

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13. ABSTRACT (Maximum 200 words)
Recently, a study correlating nondestructive evaluation (NDE) techniques with conventional destructive probe methods in a structural survey of a historical building was conducted. A comparison of NDE methods to actual physical analysis in a hands- on application was achieved. The two main areas of interest included: determining the dimensions of a wide variety of structural configurations composed of different materials and structural integrity of the walls, ceiling and floor. The use of NDE methods could substantially reduce the amount of conventional physical probing necessary for rehabilitation analysis of existing buildings.

The methods used in this study included radar, infrared, magnetic impulse, and impact echo techniques. These NDE methods were employed in the same areas that destructive analyses had been performed. Comparison of the NDE results to the destructive analyses were able to determine which methods were most suitable for analyzing different areas of a typical building structure.

Results indicate that each technique has strengths and weaknesses dependent upon their particular applications. Results from every method should be analyzed to yield a complete analysis. Every method tested was much faster and potentially more accurate than conventional coring or probing because entire areas can be completely surveyed.

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Foreword

This study was conducted for Headquarters, U.S. Army Corps of Engineers under the Construction Productivity Advancement Research (CPAR) work unit "Nondestructive Testing Techniques for Determining Structural Systems in Existing Buildings"; Funding Authorization Document (FAD) 080398, dated 17 June 1990. The technical monitors were Paul Tan, CECW-ED, and Charles Gutberlet, CEMP-ET.

The work was performed by the Engineering and Materials Division (FM) of the Infrastructure Laboratory (FL), U.S. Army Construction Engineering Research Laboratories (USACERL); Robert Silman Associates (RSA), New York City, NY; Geotechnical Survey Systems, Inc., North Salem, NH (NDE radar analysis); Center for Advanced Construction Technology, University of Illinois, Urbana, IL (NDE radar analysis); Olson NDE&T, Inc., Lakewood CO (NDE impact echo); U.S. Army Waterways Experiment Station, Vicksburg, MS (NDE magnetic impulse analysis); and Thermoscan Inc., Elmhurst, IL (NDE infrared analysis). The USACERL Principal Investigator was Robert Weber, CECER-FMC, and the RSA Principal Investigator was Marie Ennis. Dr. Paul Howdyshell is Chief, CECER-FM, and Alan W. Moore is Acting Chief, CECER-FL. The USACERL technical editor was Gordon L. Cohen, Information Management Office.

LTC David J. Rehbein is Commander and Acting Director of USACERL, and Dr. Michael J. O'Connor is Technical Director.

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1 Introduction

Background

Original structural drawings for many existing U.S. Army buildings do not exist because they were never made or because they were lost or destroyed. Subsequent modifications to a structure also are often undocumented. Documentation of the structure allows determination of live load capacity, feasibility of altering an existing building, and a deterioration evaluation of the structural components. Currently the only way to determine these structural configurations is to perform physical core sampling, physical probes, or other potentially damaging practices. For historic buildings, these test sites are required to be returned to their original condition. This type of evaluation is time-consuming and costly. The noise, dust, and inconvenience to people in the affected areas can be very great. Nondestructive evaluation (NDE) techniques could potentially mitigate or reduce many of the problems encountered with current surveys for assessing structural configurations.

NDE techniques can assess uniformity and/or discontinuities. Currently, discrete random sampling and statistics are used for structural surveys. By surveying and analyzing the NDE data from these large areas, they can be compared to the few cores required for validation and calibration of the configuration. Once the configuration of the structure has been nondestructively determined only those areas that show irregularities by NDE methods would be destructively analyzed. This would greatly improve the accuracy of the current structural survey practices.

Many building repair and remodelling projects could benefit from accurate NDEs. Structural surveys could be performed cheaper, faster, more accurately, and with less damage to the original fabric of the buildings with reliable NDE methods. The potential cost benefits from the use of NDE techniques for surveying existing building structures could be enormous.

A building undergoing a structural survey was needed to compare the results of NDE techniques to results obtained by traditional destructive analysis. A historic building is a perfect candidate because the U.S. Department of the Interior mandates that structural surveys cause only minimal damage to the historic building's original fabric (Department of the Interior 1990). With the exception of some validation and

calibration procedures, NDE does not harm any part of a structure and would therefore exceed the requirements stipulated by the Interior Department's mandate.

In a Construction Productivity Advancement Research Project by the U.S. Army Construction Engineering Research Laboratories (USACERL), Robert Silman Associates (RSA) and others, a structural survey was conducted on the historic New York State Capitol Building, Albany, for the State of New York. Additional floors between existing levels were to be built, and a survey of the existing structural configurations was necessary. This building was selected to study destructive versus nondestructive assay methods.

Objectives

The objectives of this work were (1) to assess NDE techniques currently on the market that could be used in a structural survey capacity, (2) to directly compare the structural configurations determined by NDE methods to those found by conventional survey methods, and (3) to compare the results of the different techniques to each other.

Approach

Contractors specializing in different NDE techniques were contacted and their particular NDE methods were discussed for applicability in structural surveys. After analyzing the ability of each method, four were chosen for this study: pulse-echo radar, magnetic impulse, infrared imaging, and impact echo. These NDE methods were employed in the same physical areas where conventional destructive analyses had already been performed. Comparison of the NDE results to destructive analyses results helped determine of which methods were most suitable for analyzing specific areas of a typical structure. By comparing the results for each location the capacity of each method for profiling the physical structure of vastly different structural configurations was determined.

Four typical structural configurations in the Capitol Building were chosen as test sites. These configurations, listed below, represent some of the structural types found throughout the test building:

1. Metal column in masonry/granite wall (Figure 1*)
2. Floor configurations (Figure 2)
3. Air flue/duct in exterior wall (Figure 3)
4. Metal cramps/anchors in exterior walls (Figure 4).

These four structures were chosen because they can potentially differentiate the different capabilities for each NDE method used in this study. As seen in Figures 1–4, the structures vary in material composition, thickness, physical geometry, and metal configurations. NDE results found for these structures were compared to those found by conventional survey practices.

Mode of Technology Transfer

Technical data from this study will be incorporated in *Preservation Briefs*, a publication series of the National Park Service, and standards of the American Society for Testing and Materials (through ASTM Committee E-6, Subcommittee on Standardization of NDT Technologies). The findings of this work have been published in conference proceedings of The International Association of Bridge and Structural Engineers (Mocchi 1993), the National Science Foundation (NSF) Center for Nondestructive Evaluation (Review of Progress in Quantitative Nondestructive Evaluation, San Diego, CA, July 1992), and others. Additionally, Robert Silman Associates will present the results at the Graduate Schools of Architecture at Columbia University and the University of Pennsylvania.

* All figures may be found at the end of the report, starting on page 25.

2 Test Equipment and Procedure

Pulse-Echo Radar Systems

The basic concept behind pulse-echo radar is the transmission of a known electromagnetic signal into a region and then the recording of the returned echoes to obtain information about the region. The transmitted signal is usually a square pulse modulated by a carrier frequency. The echoes originate from interfaces within the region that reflect or scatter the incident signal. From analysis of the echoes some aspects of the nature of the region and its contents can be determined. If there are multiple scatters, then one major goal of the radar system is to be able to resolve them. This capability is possible only if the echoes from the scatters are not overlapping to the extent that the echoes are indistinguishable. Hence, the narrower the transmitted pulse, the better the resolving capabilities the radar system will have.

The principal considerations for the selection of a radar system for data acquisition are the pulse bandwidth and the antenna beam width. For synthetic aperture imaging in which high resolution is desired in both the azimuthal and range directions, a wide pulse bandwidth and a wide antenna beam width are desired. However, a radar system with these characteristics does have limitations. With a wide beam width, the transmitted power is spread over a larger area reducing the reflected energy from any given scatter. Also, in many applications attenuation becomes a problem at any high pulse frequencies. The goal is to obtain synthetic aperture pulse-echo data from concrete and masonry structures to provide information about the location of subsurface occlusions such as air voids and metallic materials embedded within. The operating frequency of the antenna must be low enough so that attenuation is negligible at the desired penetration depth. For this application a radar system designed for geophysical applications provides acceptable synthetic aperture data.

The radar system used in this study was a Subsurface Interference Radar (SIR) System 8 manufactured by Geophysical Survey Systems, Incorporated of Hudson, New Hampshire. The radar system operates in monostatic mode and consists of three main components: a control unit, a data recorder, and a single transducer. The transducer operates at a frequency of 900 MHz. The pulse repetition rate is fixed at 50 kHz; however, the SIR System 8 allows scan rates of between 0.4 and 51.2 scans/s. The length of the scan is adjustable from 0 to 400 ns. The gain of the radar is exponentially

adjustable so that the echoes received later in time will be amplified more than those received earlier. The compensation is required before digitizing to prevent signal saturation from targets closer to the radar antenna.

Magnetic Impulse

A Profometer 3 steel detection instrument (pachometer) was used for magnetic impulse testing. Magnetic flux lines were transmitted into the material as the instrument's probe was moved over an area where steel members were suspected (McDonald 1991; McDonald and Alexander 1991). Upon encountering steel material, there is less resistance to the flux lines. The decreased resistance at this area produces an increased magnetic field strength that is recorded.

Infrared Imaging

Infrared inspections used video cameras capable of recording infrared radiation. An Inframetric Model 600 infrared camera was used to record the temperature differentials while Thermogram software was used to process the raw data. Entire walls, floors, or ceilings were scanned and variations in thermal radiation at the surfaces were recorded continuously on video tape (Olson Engineering, Inc. 1992). The data were analyzed and individual photographs were produced for each area tested. The grayscale photographs were color-enhanced to show the temperatures at the structure surface.

Impact Echo

Impact Echo (IE) testing was conducted by striking the surface of a test area with a small (0.2 lb) instrumented impulse hammer. An accelerometer mounted with a couplant to the test surface received the reflected energy (Thermoscan, Inc. 1992). The pounds force of the impact and the reflected wave energy were measured and recorded. Because the reflections are more easily identified in the frequency domain, the time domain test data of the hammer and the receiver are processed with fast Fourier transform operations by the dynamic signal analyzer for frequency domain analysis. In addition, ultrasonic pulse velocity (UPV) testing was done in the same areas as the IE. UPV is an ultrasonic test for evaluating concrete quality and integrity in accordance with ASTM C597-83. The equipment consists of a transmitter, receiver, UPV meter, amplifier/filter, and a recording oscilloscope. The test consists of passing an ultrasonic compression wave pulse a known distance through concrete. The pulse

velocity and amplitude are reduced by the presence of cracks, honeycombing, and other flaws.

Test Procedures

The NDE technicians surveyed several different areas of the building. These areas were chosen by RSA structural engineers present as typical configurations found throughout the entire structure. The NDE surveys were performed after conventional destructive practices were performed on the areas. Data from each technique was recorded for each area. An NDE survey producing no data was noted as well. A comparison of the NDE results to the conventional survey was performed. Any errors in the NDE results were noted.

Every method required refinement of the raw data recorded for each test area. Most techniques required sophisticated computer enhancement to produce the final results. A large part of the analysis time was spent in the laboratory deciphering the noise from the signal and enhancing the data to determine the required measurements.

3 Test Results and Discussion

Each NDE technique yielded excellent results in certain areas or configurations. However, none of the methods tested provided excellent results for all of the configurations analyzed. Table 1 summarizes the results for each method at the various structural configurations. The results are given as excellent (E), marginal (M), or no (N) data produced.

Table 1. Results of Each NDE Method for Selected Test Areas.

STRUCTURE	RESULTS FOR NDE TECHNIQUES			
	RADAR	IMPACT ECHO	MAGNETIC IMPULSE	INFRARED
METAL COL-UMN	E	E	E	N
FLOOR	E	N	M	N
FLUE	N	N	N	E
ANCHORS	M	M	E	N

As can be seen in Table 1, no single technique produced excellent results for detecting all subsurface features. Each method had different strengths and weaknesses that were characteristic to the specific NDE technique. It was found that the three penetrating methods (radar, IE, and MI) were very sensitive to changes in material composition. Infrared, which was a non-penetrating technique, was limited to applications where the surface to be inspected showed a temperature differential. The results and interpretations for each method are discussed in detail in the following sections.

Discussion of Individual Results

Radar

Radar produced the best overall results for this type of building. It penetrated very thick sections much more readily than any of the other methods. Because this building is very massive throughout, the superior penetrating ability of radar proved to be very effective for this study.

The principle of radar is based upon detecting differences in dielectric properties of materials. This allowed the engineer to determine the profiles of the configurations throughout the building. It was most effective when the dielectric properties were very different, such as metallic I-beams inside masonry/granite structures. However, it was also the only method that was able to penetrate and profile the shallow masonry arches found in the floor structures. The interface between the bottom of the masonry floor and the surrounding air was easily detected by radar providing a means to accurately profile the thickness of the floor structures.

The structural configuration of the metal column in the granite/masonry wall is shown in Figure 5 along with the dimensions determined by analysis of the radar data. The radar survey was conducted on the outside of the building through the granite facing. The location of the beam was determined as seen in Figure 5. The location, orientation, depth of cover, and size of the I-beam was determined by the use of a data manipulation program developed at the University of Illinois Advanced Construction Technology Center (ACTC), by J. Mast and J. Murtha. A key feature of this program enabled the data to be presented as a function of distance rather than time allowing the structural engineers to interpret the data much more straightforwardly than would otherwise have been possible. The resulting grayscale reflection profile is shown at the top of Figure 6. The backward propagation method of analysis image is shown on the bottom of Figure 6. The granite/masonry interface is visible in the image due to the mortar or air content in the masonry. The scan was taken near a window opening and the corner is visible as a strong reflection.

The configuration for the high arch floor structure is shown in Figure 7. The radar was towed over the floor and the resulting grayscale image is shown at the top of Figure 8. Using the backward propagation method produces the spatial image at the bottom of Figure 8. Only the apexes of the arch are reconstructed because they are the only reflectors of the incident beam. The rest of the arch only scatters the beam energy. The spacing between and the depth of the reinforcement, the masonry arches, the thickness of the concrete surface layer, and the location of the steel I-beams are determined and shown in Figure 7.

In contrast to the high masonry arch, a low masonry arch was investigated. These arches are twice the span but half the height of the high arch. Figure 9 shows the configuration with the associated dimensions. The grayscale image of the structure is contained in the top of Figure 10. The backward propagation image shows the interface between the concrete and masonry, the location of the top flanges of the beams, and spacings of the beams.

At one test area of the building a newer flat-slab floor construction was found next to the low arch type construction. The structural configuration as well as the dimensions is shown in Figure 11. From the top there was no way to determine which part of the floor was shallow masonry arch and which was flat slab construction. Radar detected the change from shallow masonry arch to the flat-slab floor structures very easily. The grayscale of the transition area is at the top of Figure 12. The backward propagation image is at the bottom. The small, sharp spots under the label "concrete" are produced by the metal mesh under the flat concrete slab floor. The left side of the image shows the shallow masonry arch structure.

The radar method was also used to locate flues inside of a masonry wall. The radar could not locate the flue shown in Figure 4. At a different site where two adjacent flue pipes were embedded in the wall, the radar was able to detect the location and size. Figure 13 shows that configuration and the deduced dimensions. Figure 14 contains the grayscale image and the backward propagation image of the flue inside the wall. The flues are not perfectly round in the lower image. This could be due to a non-uniform tow velocity caused by hand towing or by a change in the amount of air space in the masonry wall.

Since radar was successfully used to determine two other air flue configurations in different areas, the former explanations may be more accurate. The fact that the antennae must be physically passed over the entire test area to analyze the hidden configurations was a moderate limitation for radar.

Radar readily detected the location of the anchors in the walls, but was unable to determine the material composition. Radar could not determine by reflecting signals off of hidden components if these components were voids, metal, or just a strong interface at the locations. The inability to determine the characteristics of a material was another moderate limitation of the technique.

Magnetic Impulse

Magnetic impulse (MI) was limited to structures having ferromagnetic components. Structures such as the ceramic lined air flue inside the masonry wall were not

detectable. However, most of the structures had some kind of metal inside the configurations. MI was used successfully to determine the location and depth of cover for most of these structures.

Figure 15 shows the MI results for the metal column test. The location of the column in the wall was accurately determined.

This accuracy was repeated in locating the floor structure's metal framing as seen in Figure 16. The depth of cover could not be determined on a consistent basis and therefore is not included. It is not known why the results did not yield repeatable data when determining the depth of cover.

The physical geometry of both the shallow masonry arch and flat concrete slab configurations could not be measured. The reinforcing metal mesh under the flat-slab structure produced a strong signal and obstructed the signals from deeper in the floor making it impossible to analyze the physical shape of the floor.

MI was the only technique that located and recognized the metal anchors in the external walls. This ability to recognize metallic components proved to be one of the method's stronger attributes.

Infrared Imaging

Infrared imaging (IRI) was the only method used that did not penetrate the structures being investigated. The surface analysis of the structures made it extremely fast and simple to use. Although limited to structures that had internal temperature differentials, infrared was extremely useful in analyzing types of structures that the other methods could not. Some of these included water-damaged walls on the exterior of the building, hot/cold water lines in the walls, and structural changes from past remodeling. These will be discussed further in the following sections.

IRI's inability to provide data for structures that did not produce temperature differentials (i.e., the metal column, floor structure areas, and metal wall cramps/anchors) was a severe limitation for most of the areas analyzed. However, infrared was the only technique able to scan entire walls in a single pass, therefore allowing it to detect the air flue/duct in an upper story exterior wall.

Figure 17 is a photograph of the wall where the masonry flue is embedded. Figure 18 is the color-enhanced photograph of the flue area. It clearly shows a warmer section of the wall showing the location of the hot air flue embedded in the masonry wall. No other method was able to detect this flue. The entire wall and span of the flue was

tracked by the infrared method in a matter of minutes. This method was extremely fast compared to the other NDE techniques, while much larger areas were scanned in one pass. Additional configurations were detected that had previously been unknown because of the wide area covered.

Such a configuration was detected while scanning the air flue test area. The infrared camera detected the original structure of a window on the fifth floor. Figure 19 shows the window as seen from the interior. Figure 20 shows the infrared image which clearly depicts the thermal outline of an arch that is not seen from the inside of the building. The arch was once part of a masonry arched window structure that has since been covered over by a plaster wall. The infrared method shows the masonry arch over the window. This configuration was not detected until infrared was used on this part of the building.

The ability to quickly scan entire structures was also put to good use in analyzing entire wall sections of the exterior for hidden water damage. Figure 21 depicts several sections of the exterior wall exhibiting substantial staining. It was thought that water damage was a possible factor in this staining and infrared was used to determine if this was the case. Figure 22 clearly demonstrates a substantial temperature difference between the stained and unstained portions of the wall. Because waterlogged stone will conduct heat more readily, this clearly indicates that the stained portions are water damaged.

Impact Echo

Impact echo (IE) is very sensitive to interfaces between different materials, and between materials and air inside structures. The material must be solid, free of defects, and generally in good physical condition before IE can transmit signals through a structure. Flaws, internal interfaces, and deteriorated materials produced very strong reflected signals. No other method was as sensitive to the material condition of the structures as IE.

Results for the metal column embedded in the granite/masonry wall are shown in Figure 23. The location and the depth of cover over the beam was accurate. The bonding between granite and the masonry wall was adequate to transport the signal into the masonry wall, but the signal was unable to penetrate completely to the back wall. Orientation and size of the beam could not be determined.

IE was unable to produce consistent results for the floor structures. It was determined that there was not an adequate bond between the two concrete layers to transport the signal into the second type of concrete. Thus, the metal I-beams and the profile of the

bottom of the floor structure could not be found. The problem of weak bonding across interfaces was a serious limitation for most of the structures encountered by IE.

IE could not produce any results for the air flue embedded in the masonry wall. Due to the soft nature of the plaster material covering the masonry wall, the signal was completely adsorbed and not transferred to the masonry interior.

The location and depth of cover for the anchors in the exterior walls were found, as seen in Figure 24. However, as with the radar technique, the material composition could not be determined.

In addition to the four main test areas studied, IE was also used to find flaws in solid, homogeneous granite columns. The depth and size of the flaw was detected by IE while UPV was used to determine the orientation of the flaw.

Summary Discussion

Limitations of NDE Surveys

This study reconfirmed that no single NDE technique can be used to perform a comprehensive building examination by itself. Each technique has strengths and weaknesses. To form a comprehensive survey of the structure, information from a variety of techniques would have to be pooled together to provide a complete picture.

A problem common to every method was the interpretation of the signals received from the testing procedure. Signal interpretation for each process depends to a great extent on the expectations or experience of the operator. Odd or unexpected structural configurations could not be analyzed by the average NDE operator. Each process requires a database of information about signal strengths and conditions to aid in data interpretation. This database should contain calibration and validation information about reflected signals based on interfaces encountered, group and size distribution, and material propagation rates. This information could be accessed through the operations program and would assist the operator and engineer in data signal interpretation for each area investigated. Without this database, signal interpretation is "hit or miss." In the case of the radar evaluation, the system operator had enough background in the use of the system with various building materials from the development stages of the data manipulation software.

The New York State Capitol Building is not a typical structure. This building represented a worst-case scenario for the techniques used in this study, except radar.

The massiveness of the walls and floors, little or no metal framing, and a great variety of configurations and materials used in the construction of the building presented many obstacles to accurate survey of the structures using any of the techniques.

An important limitation of radar and IE was the difficulty in predicting proper frequencies required for penetrating a particular structure, even when the materials present were known. This is a calibration issue. The signal response depended on such factors as the physical configuration of the structures, the amount of ferrous materials, the bonding between interfaces, the material conditions, and the composition of the entire test area. Extensive calibration data of signal responses for material combinations and standard configurations typical of the structure under study is required to minimize the interpretation mistakes when surveying a structure.

Equipment for both the radar method and IE was bulky and required considerable skill to operate and interpret the results. Calibration of the signal response to the various materials, accessory to ensure a proper signal interpretation, required much time.

Radar also had trouble penetrating surface materials containing ferrous materials. Materials such as wire mesh, red-tinted ceramic tiles, and electrical conduit inside the structures cluttered the response signal. Often these thin ferrous materials would block the signal completely and the radar could not penetrate the interior of the structure.

IE had limited success in determining the physical configuration of multi-component structures because of the technique's extreme sensitivity to interfaces. Unless the bonding across an interface was extremely tight, the signal could not penetrate to the adjacent material. Most of the structures analyzed had numerous interfaces, making the signal interpretation difficult. Determining the physical profiles of structures such as the shallow masonry arch and the flat concrete slab configurations was not possible for IE. Also, inelastic materials such as plaster walls or carpeted floors were unable to transfer the signal into a test area. It was found that IE was best suited for homogeneous material configurations such as granite columns, or solid walls such as the anchors test areas.

MI was limited to the detection of ferromagnetic metals. The typical depth for magnetic impulse generally ranged from about 9 to 12 in. This range was affected by the size of the object being detected; larger objects could be detected at greater depths, and smaller objects only near the surface of a structure. The signal was also affected by electrical conduits, ferrous-based paint, and other extraneous objects embedded in the structures.

Infrared was the only method that did not penetrate the surface of a structure to determine internal configurations. Components exhibiting temperature differentials were detectable, such as air ducts, water lines, internal heating devices, or separate construction materials having different heat transfer rates. This capacity to detect differences in rate of heat transfer is why IRI is used to view structures. This result is achieved by scanning the structures on the opposite side of a large temperature differential (i.e., scanning the inside wall of an air-conditioned building on a hot day).

The New York State Capitol Building had walls and rooftops that were much too thick to provide significant temperature differentials. The infrared contractors assisting in this study concluded that 24–30 in. is the maximum thickness that infrared can analyze in the materials encountered in this job. Anything thicker than this will have extremely slow rates of heat transfer, and consequently the infrared image will be compromised. This was apparent when scanning interior structures. Very large temperature differences on either side of a wall are required to provide crude images of the internal configurations. Accurate imaging was not achievable in the interior structures. The New York State Capitol Building provided a worst-case scenario for the infrared technique.

Benefits of NDE Surveys

Radar provided excellent results for most of the structures studied. Once the proper frequency was established for a particular test area, the results were very good. Radar has also been shown in other studies to be effective in imaging less massive structures. A Federal Highway Administration study (Joyce 1985) has shown radar can accurately resolve re-bar reinforcement positions in bridge spans. Re-bar diameters as small as 2–3 cm were detected by radar with a high degree of accuracy. Thus, radar is not limited only to massive structures such as those found in the capitol building.

Radar provided much more information about interior structure than any other method tested. Using the software developed at the University of Illinois Advanced Construction Technology Center, the physical dimensions of the internal components were consistently calculated within 1 in. of actual size. No other method produced such a wide variety of accurate measurements of the physical configurations present in the tested structures.

IE's sensitivity to material interfaces was a benefit as well as a disadvantage. It was the only method that could accurately determine the differences between grades of concrete, interfaces between brick and granite, or the condition of a material. IE was much more effective in testing homogeneous materials such as solid granite or concrete. This was particularly useful in determining the soundness of round and

square granite columns, which were initially used as calibration samples. Any flaws, whether vertical or horizontal, inside the columns were detectable by IE. Detecting flaws in solid columns and determining their orientation was cited as particularly useful by the structural engineers present for the tests. For many buildings with column structures, the physical condition of the columns is of great concern. The ability to accurately and nondestructively determine the condition of the columns would be very beneficial.

Although limited to detecting only metal components, the MI technique was very useful in positively determining the location of metal objects. Magnetic impulse was the only method able to positively determine if a hidden material was metallic. Coupled with the portability and low cost of the equipment, this proved to be a very useful method. MI was also the simplest to use. The easy determination of metal framing was appreciated by the structural engineers present for the testing. These factors led the structural engineers participating in this study to purchase an MI device. They have since used this technique on other projects. Thus, MI has already progressed one step beyond the other techniques in that it has gained acceptance from structural engineers and is being adopted as a useful tool in structural surveys.

Infrared proved to be the fastest method of scanning a structure, both in application and interpretation. Radar and MI were relatively fast, requiring only manual manipulation of the antennae. IE was very slow, requiring proper placement and adhesion of the detectors. Infrared required only a quick pass of the camera to record and determine the components inside the structure. This rapid application was useful in determining quickly where infrared radiation was being emitted in a particular structure. Components such as the air flue in the masonry wall, water lines, and other sources of heat were easily found and analyzed.

4 Summary and Recommendations

Summary

Each NDE technique exhibited different strengths and weaknesses. No single method produced excellent results for all test areas studied; used together they provide a significant advantage over coring and probing, with results that are comparable.

- All the NDE techniques used in this work are available now and can be used for building structural analysis.
- The exceptional penetrating power of radar allowed it to be applied to most test areas for this type of building.
- IE was very sensitive to material interfaces, and was therefore most effective for determining the condition of homogeneous materials.
- Although limited to detecting ferrous objects, MI was very simple to use and gave definite results for detecting metal framing.
- Infrared surface scans allowed quick and easy surveys of temperature differentials on large areas such as walls or ceilings.
- The use of NDE will substantially decrease the time and effort needed for structural surveys of historic buildings with results comparable to current methods.
- The analyses are nondestructive, thus, allowing the structural engineer the freedom to analyze the most delicate structures without fear of damaging the materials.
- NDE results can quickly and accurately indicate the best locations and numbers of core samples or probes to execute, when conventional survey followup methods are required.
- This study demonstrates that NDE techniques, properly calibrated, can be used to detect and determine structural configurations in a building.
- Although these NDE technologies are not new, many had not been used in these types of applications before; each technology provided useful results in some of the cases evaluated.
- Based on the results of this study, one of the participating contractors—RSA—acquired an MI system for use in structural surveys.

Recommendations

It is recommended that the instruments and methods described in this report be used to assess the condition of historically significant structures. It is also recommended that these technologies be considered for use in surveying damaged structures following storms and earthquakes due to the reduced time and effort required, and because they are inherently nondisruptive to damaged materials. It is recommended that additional work addressing some of the limitations documented for each technique be undertaken, including the following:

1. A signal response database for various materials and configurations should be developed for all techniques. This database is especially important for radar and IE methods, which rely more than other techniques upon accurate signal interpretation.

2. The combining of NDE techniques should be pursued. By exploiting the strengths of each method, a more effective hybrid technique be achievable. A simple, user-friendly software program might be developed to superimpose data from the various NDE methods. Areas that produce a signal for each method would be strengthened, while areas that do not produce repeatable signals would be diminished, thus producing a more complete picture of any structure.

Metric Conversion Factors

1 in.	=	25.4 mm
1 ft	=	0.305 m
1 sq ft	=	0.093 m^2
1 sq ft/min	=	0.093 m^2/min
1 cu ft	=	0.028 m^3
1 mi	=	1.61 km
1 lb	=	0.453 kg
1 gal	=	3.78 L
1 psi	=	6.89 kPa
1 µm	=	1×10^{-6}m
°F	=	(°C x 1.8) +32

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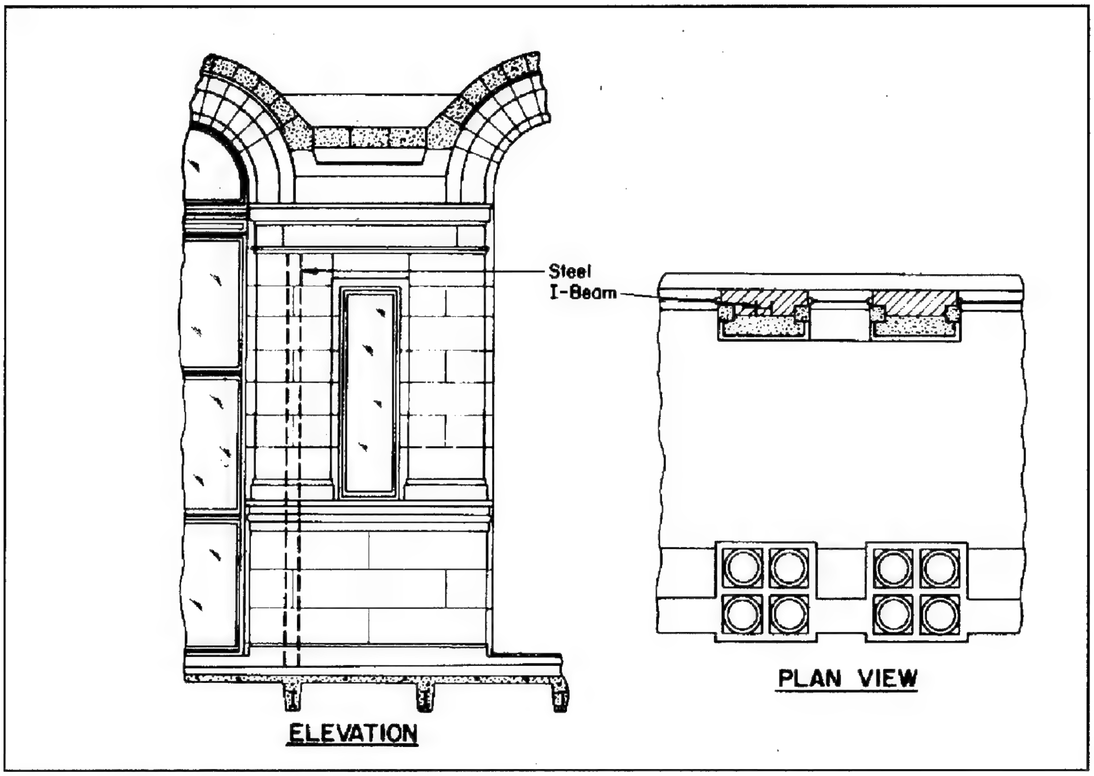


Figure 1. Metal column in granite/masonry wall.

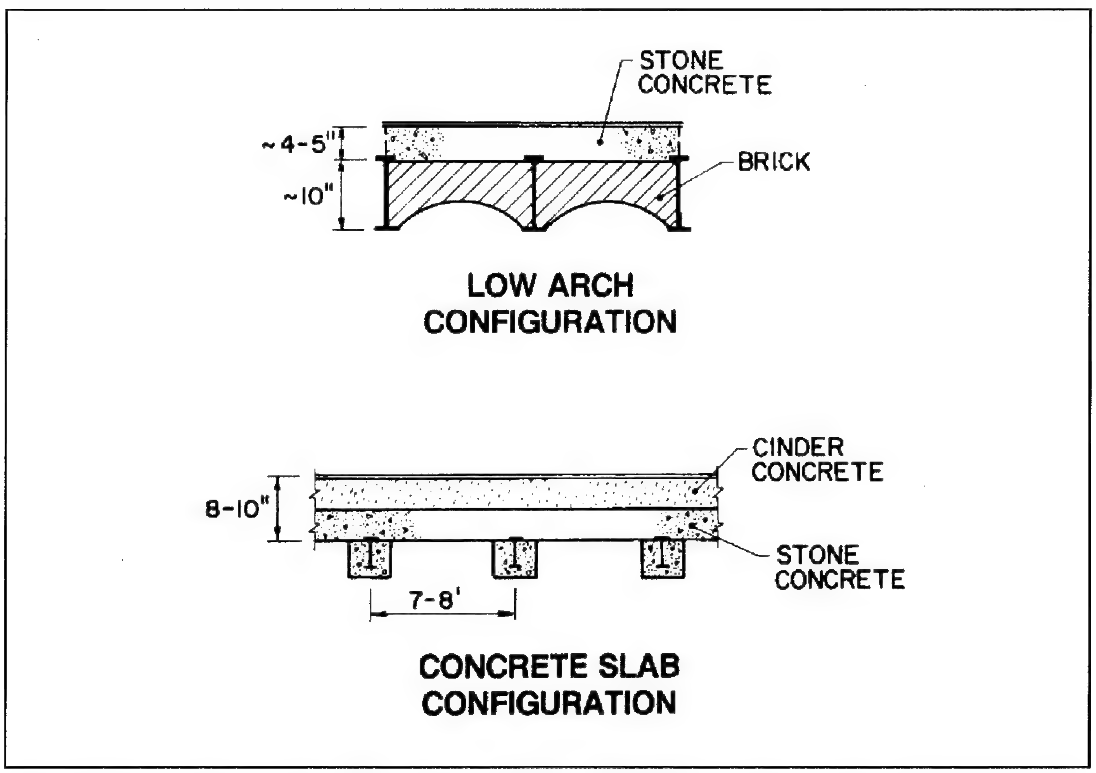


Figure 2. Shallow masonry arch floor construction and flat slab floor construction.

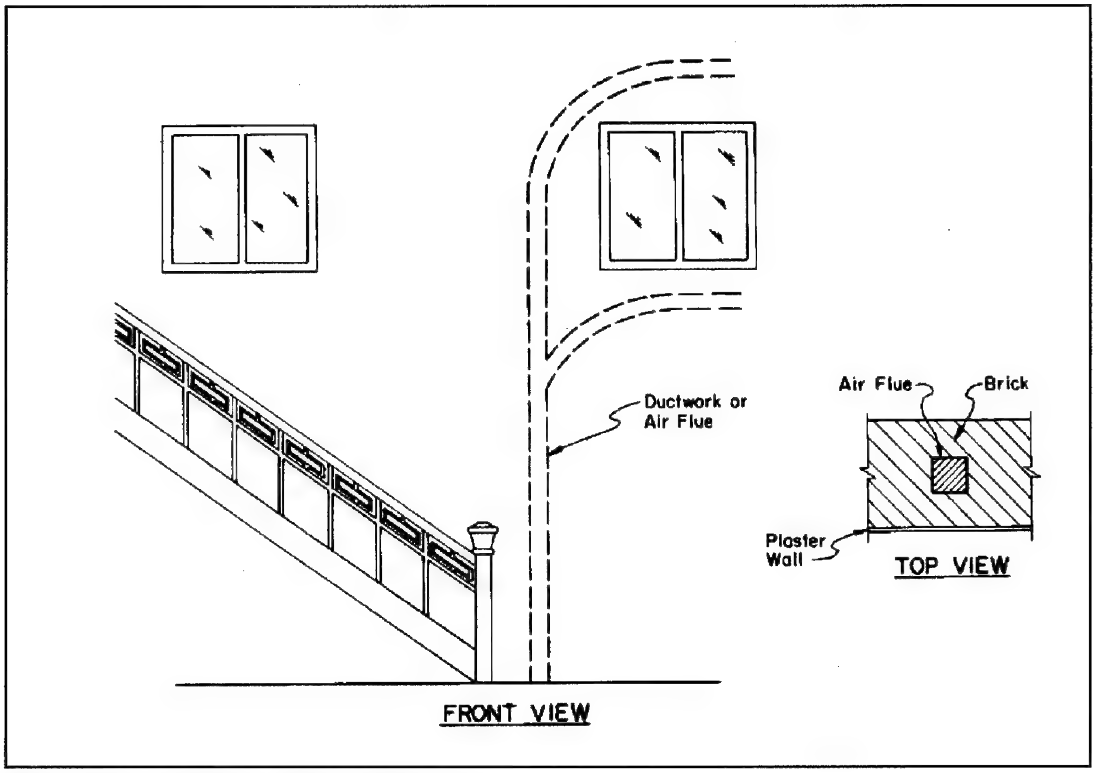


Figure 3. Air duct/flue in solid masonry wall.

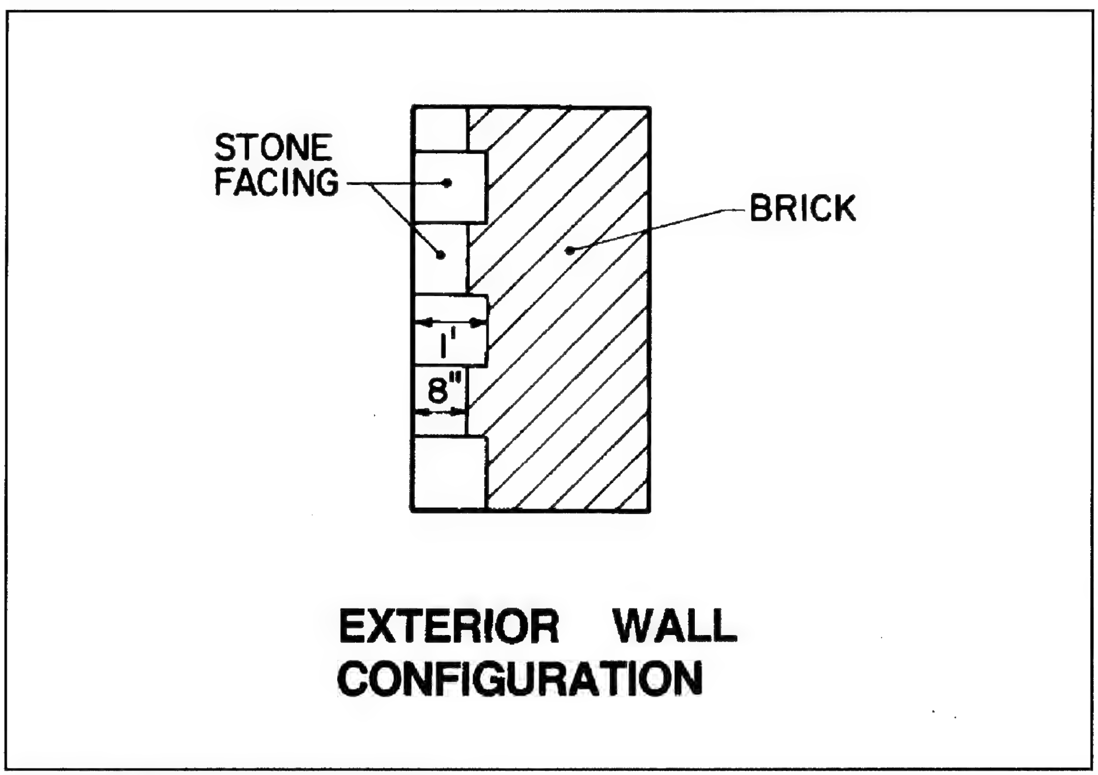


Figure 4. Metal anchors in exterior walls.

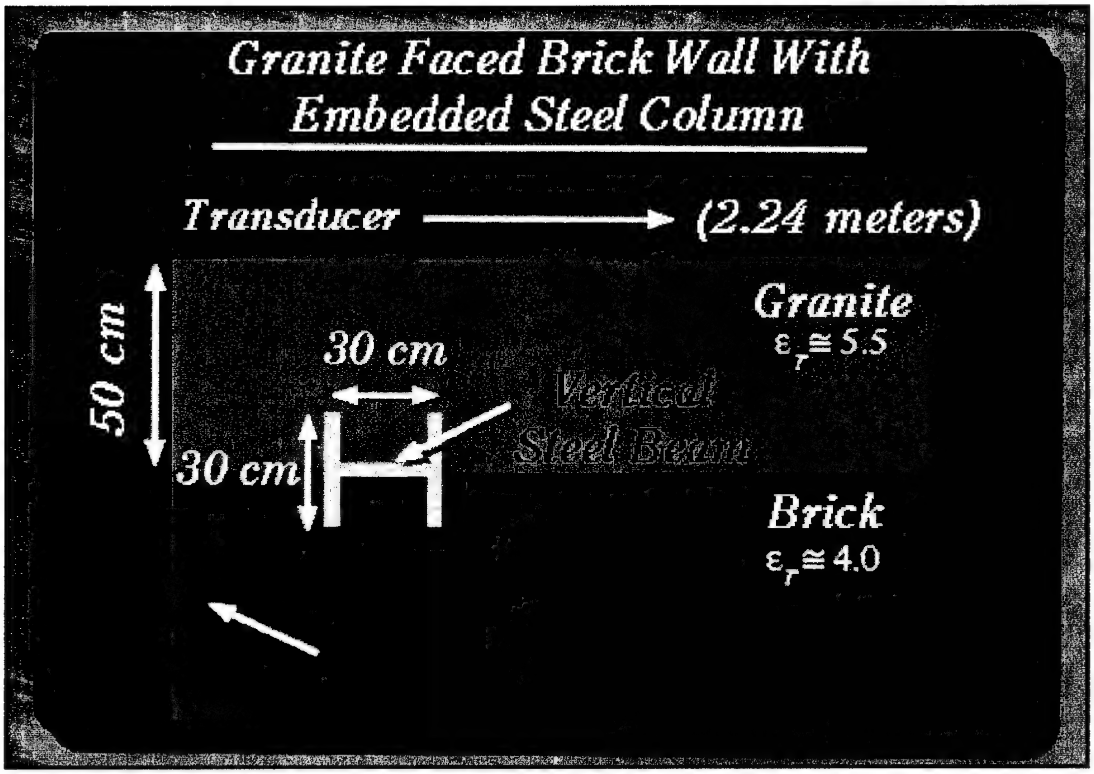


Figure 5. Steel column inside granite/masonry wall with dimensions as determined from radar data.

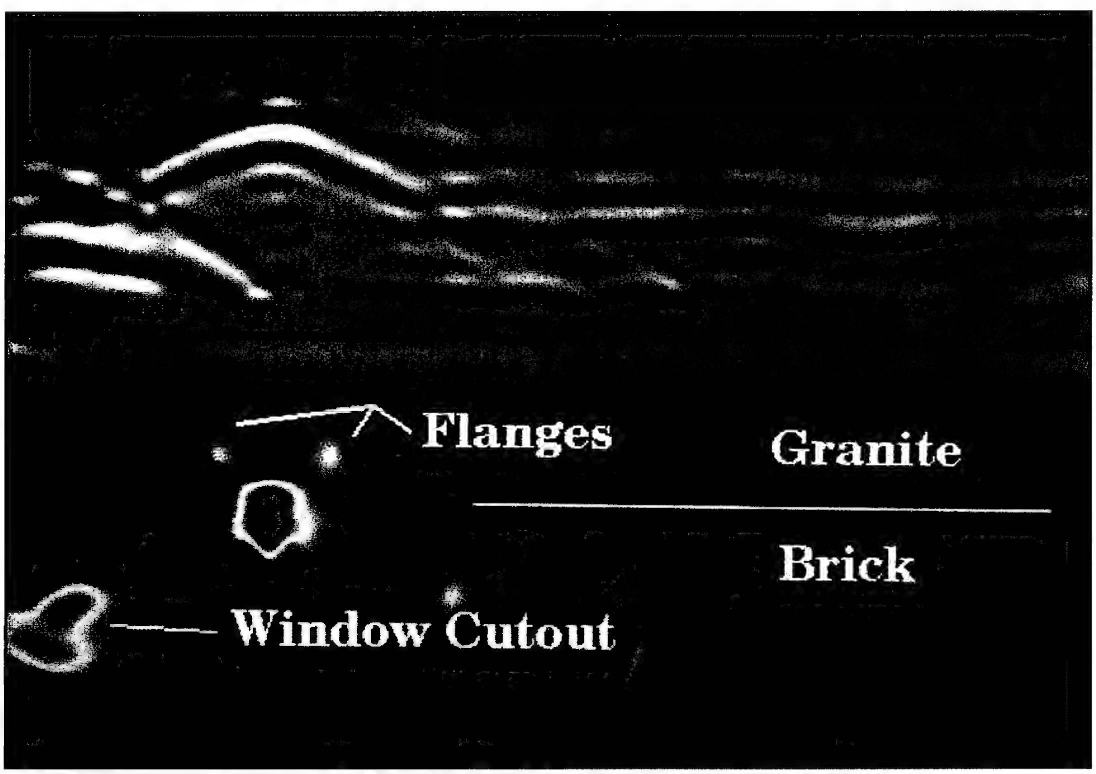


Figure 6. Grayscale image from radar data for column in granite/masonry wall (top) and backward propagation image of the data (bottom).

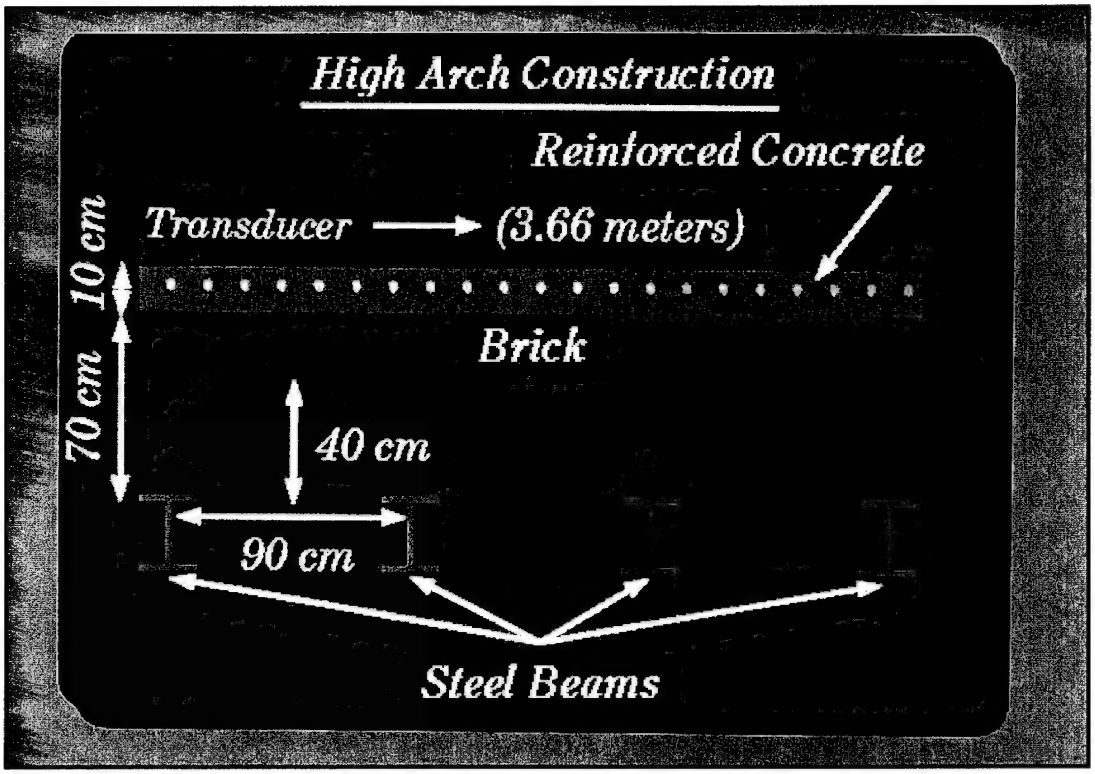


Figure 7. High arch floor configuration with dimensions as determined from radar data.

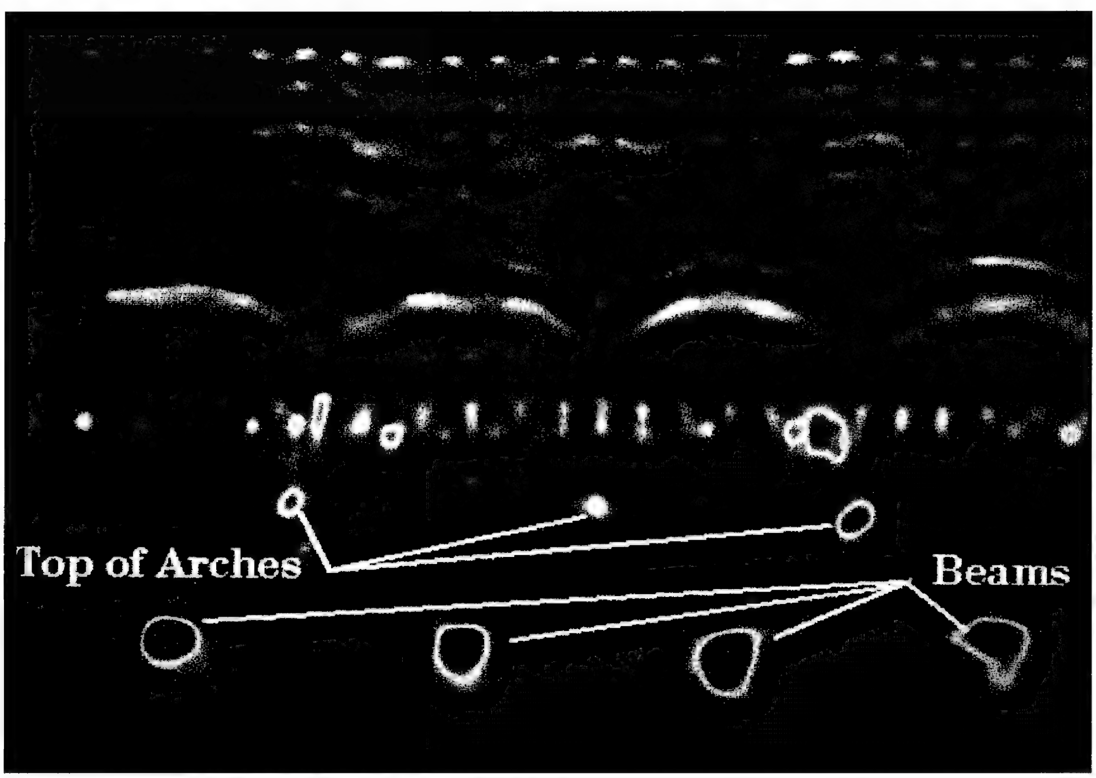


Figure 8. Grayscale image from radar data for high arch floor (top) and backward propagation image of the data (bottom).

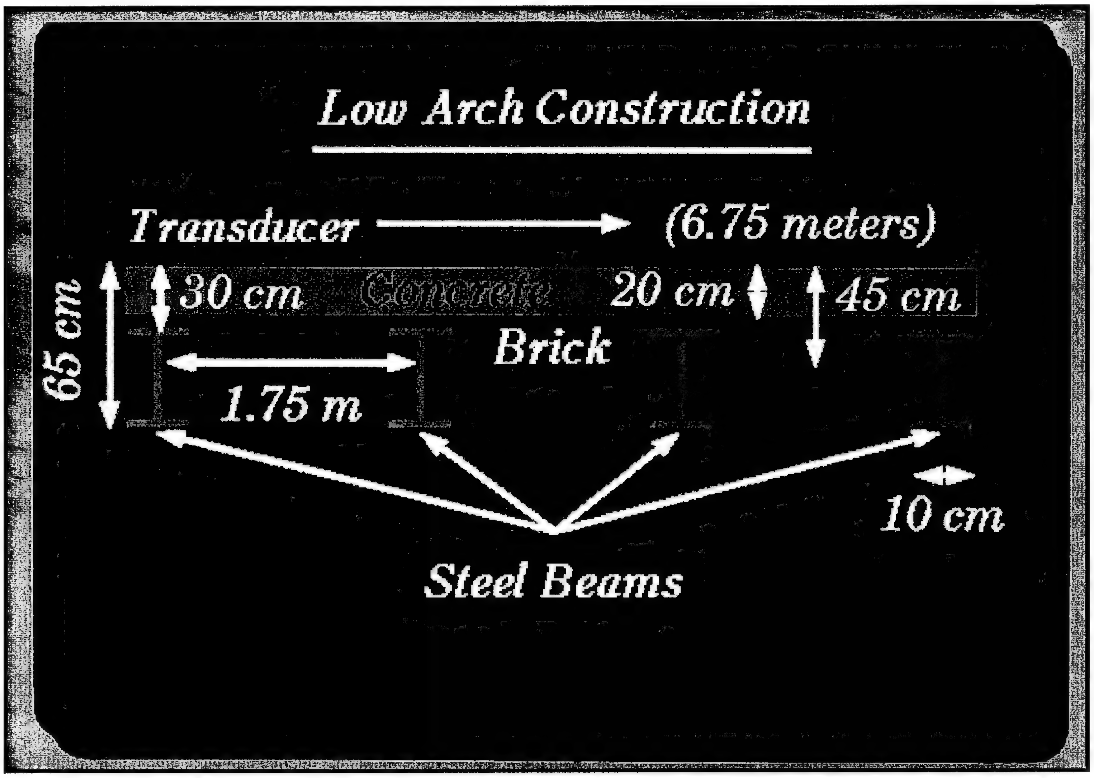


Figure 9. Low arch floor configuration with dimensions as determined from radar data.

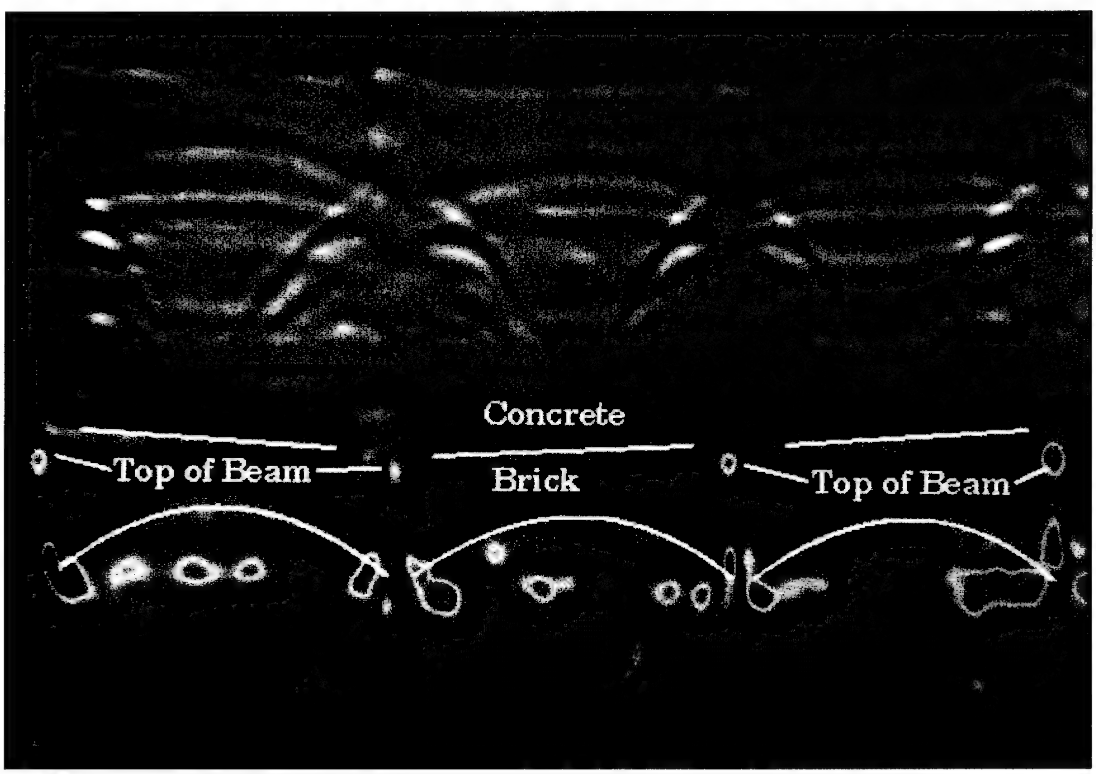


Figure 10. Grayscale image from radar data of low arch floor configuration (top) and backward propagation image of the data (bottom).

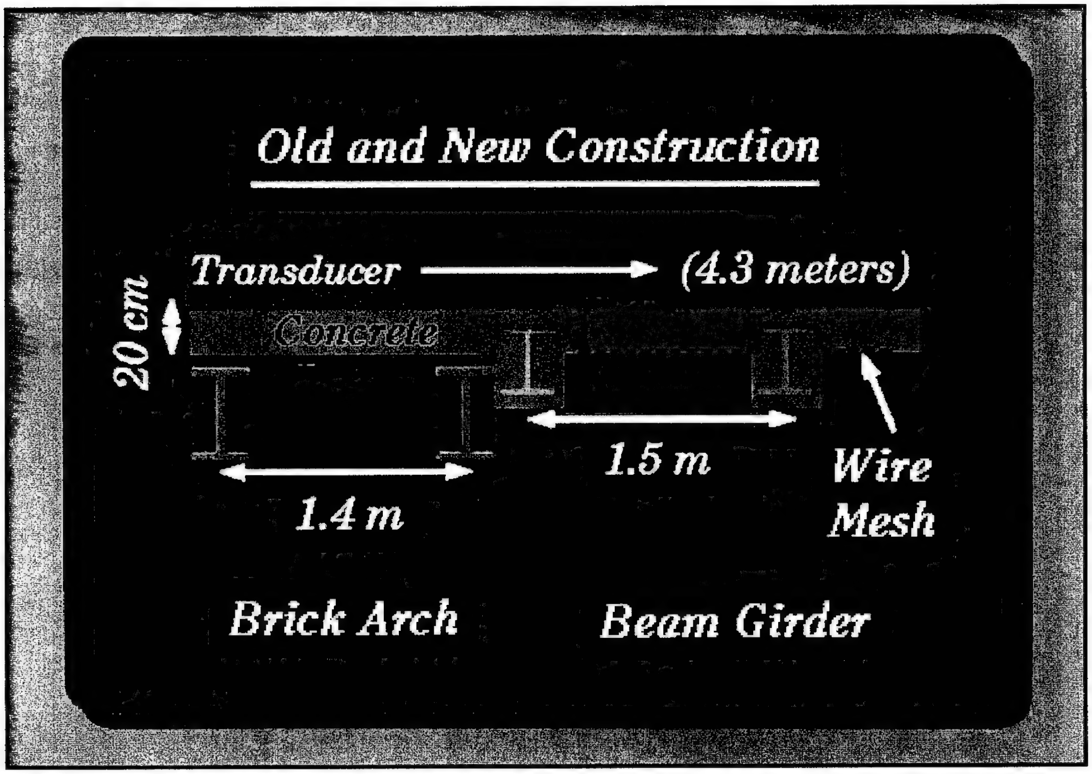


Figure 11. Transition between low arch and flat-slab construction with dimensions as determined from radar data.

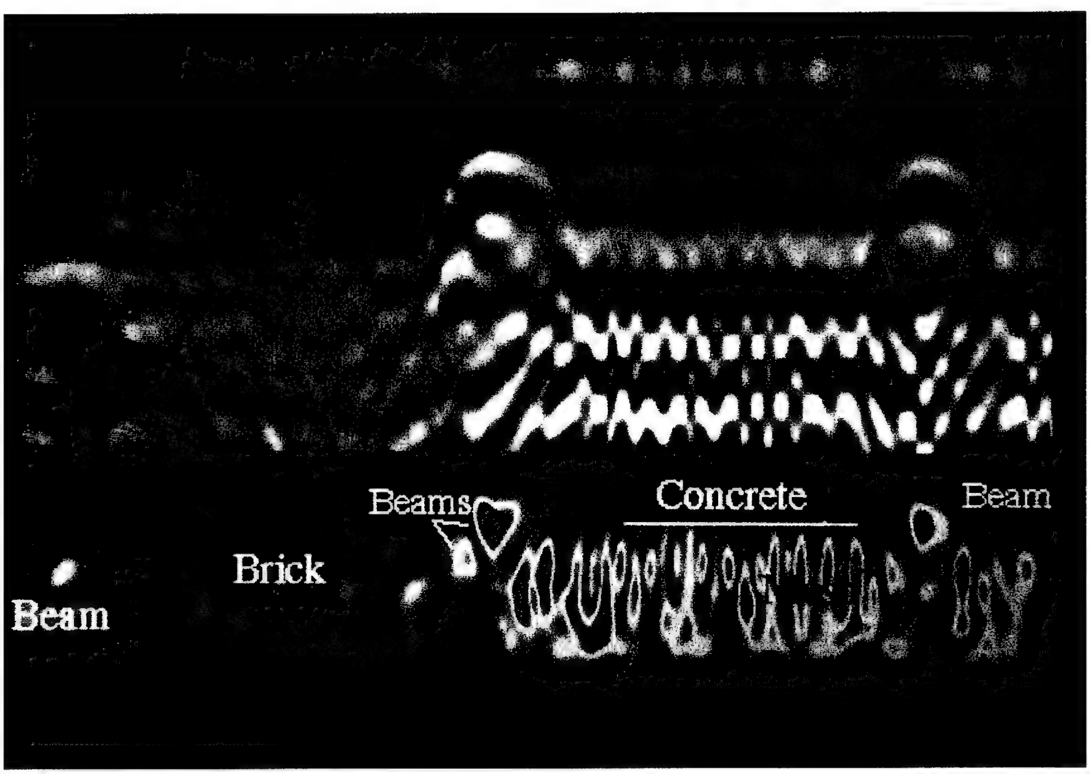


Figure 12. Grayscale image of the radar data for transition between low arch and the flat-slab floor configurations (top) and backward propagation image of the data (bottom).

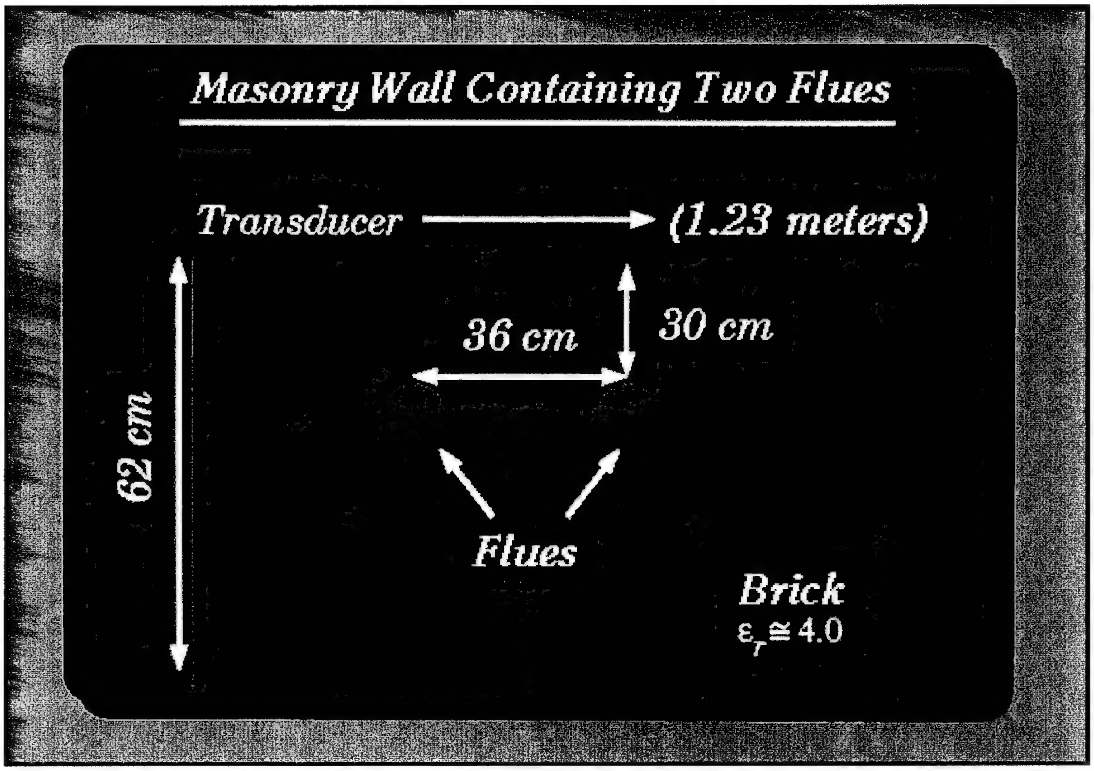


Figure 13. Flue configuration in masonry wall with the dimensions as determined from radar data.

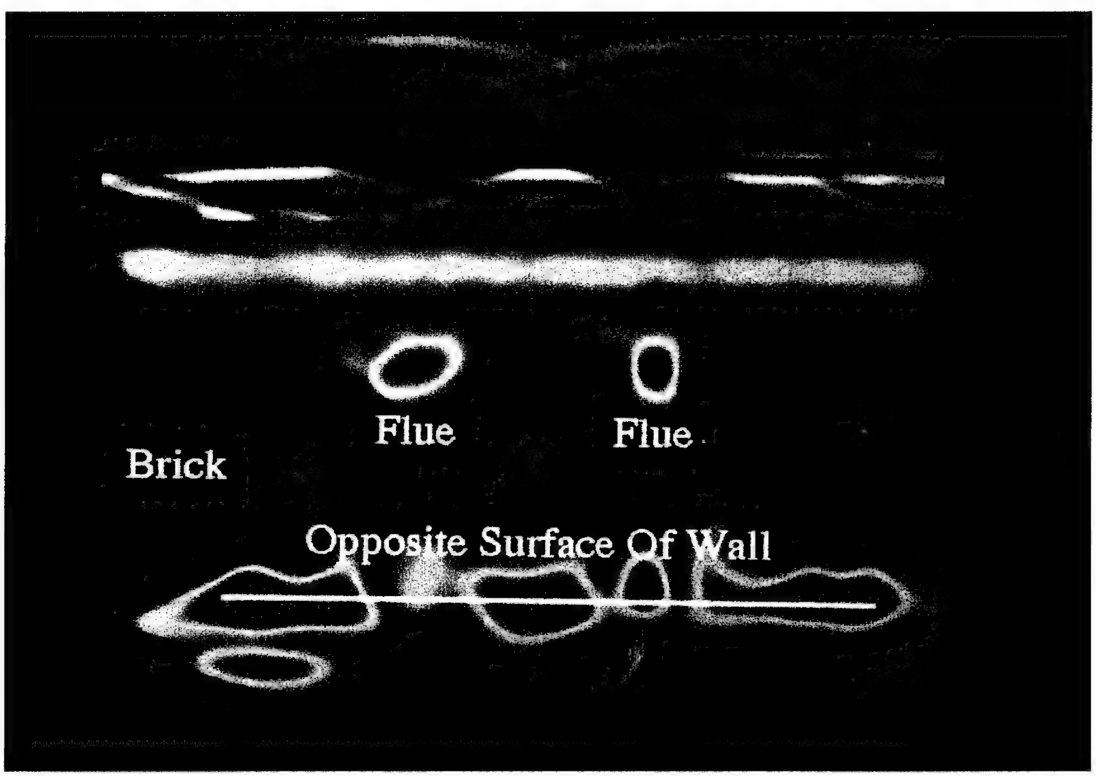


Figure 14. Grayscale image from radar data for masonry wall containing two flues (top) and backward propagation image of the data (bottom).

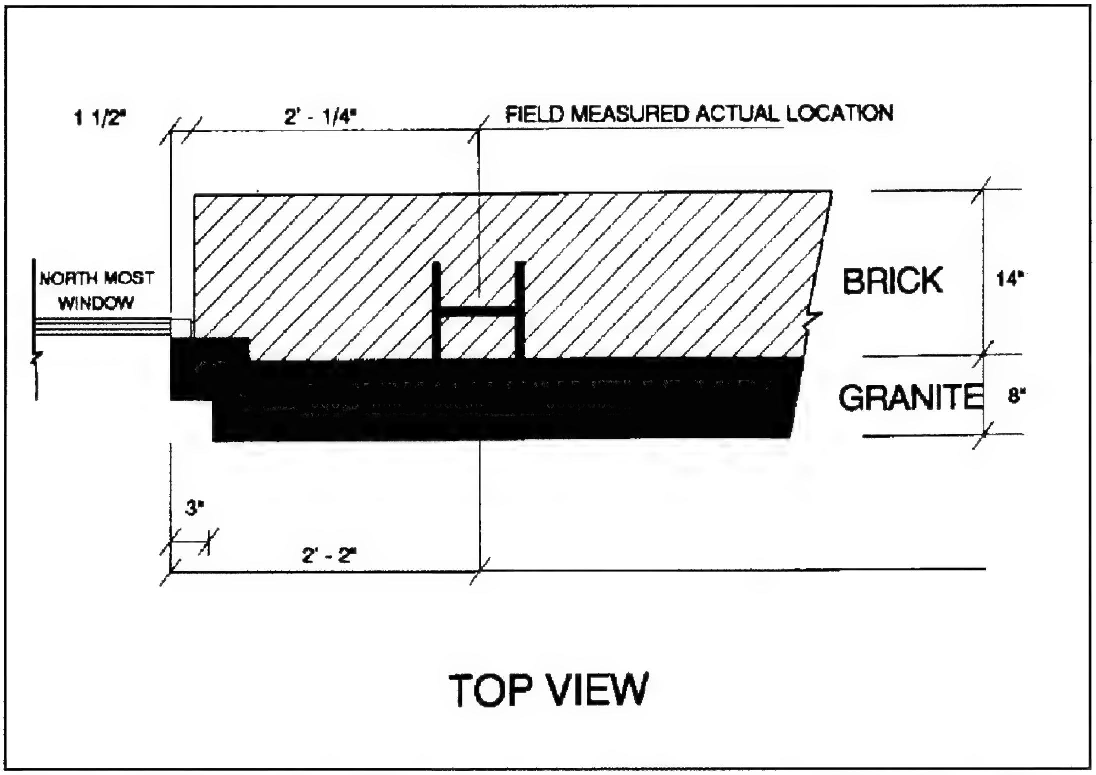


Figure 15. Metal column in granite/masonry wall with dimensions as determined from magnetic impulse data.

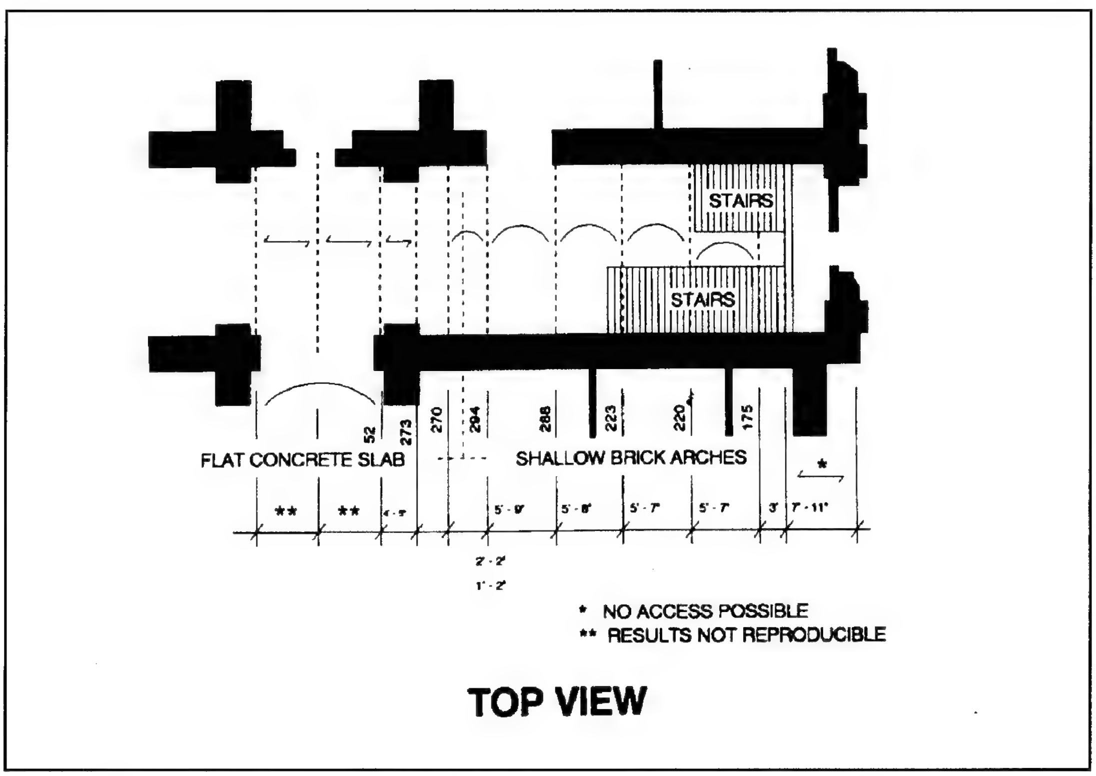


Figure 16. Transition of low arch and flat-slab floor structures with dimensions as determined from magnetic impulse data.

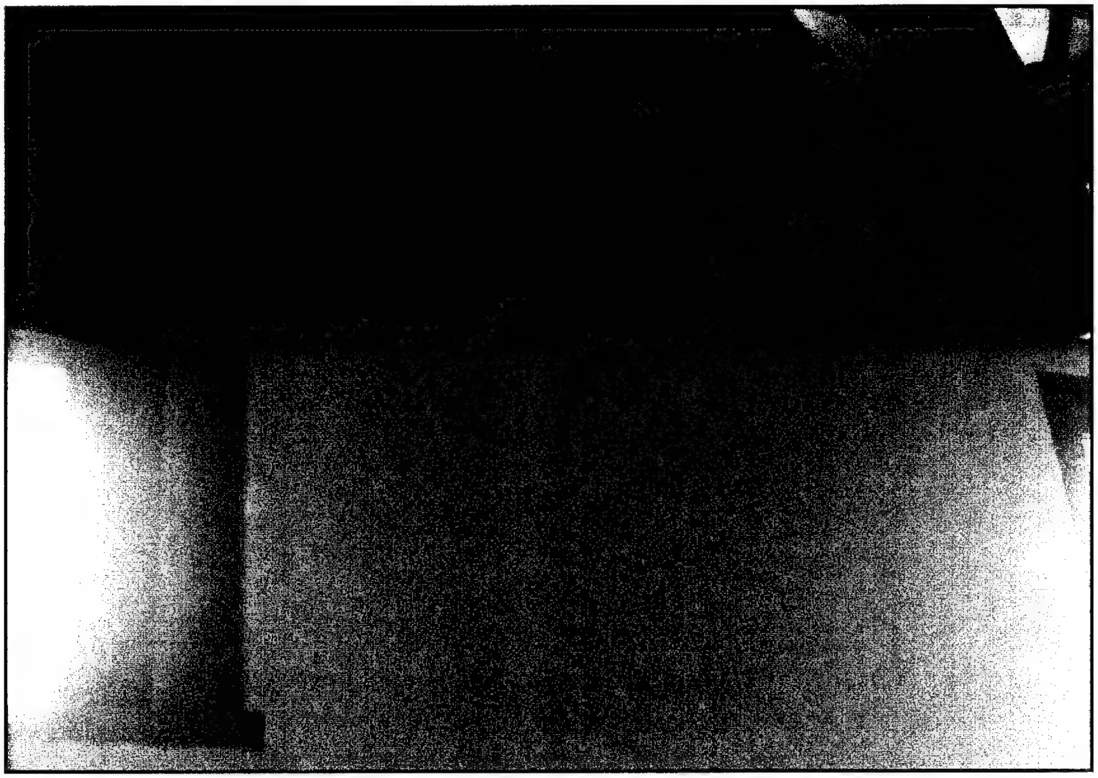


Figure 17. Photograph showing wall area where embedded flue pipe is located.

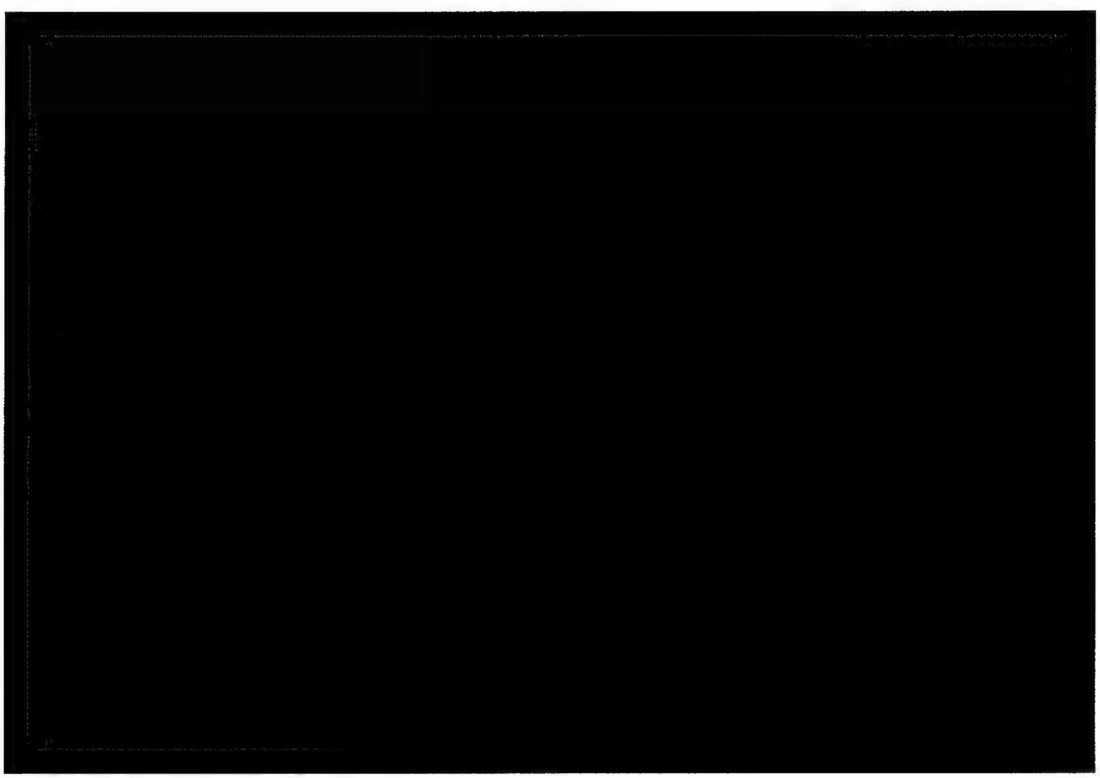


Figure 18. Color-enhanced infrared image of wall showing higher temperature indicating embedded flue.

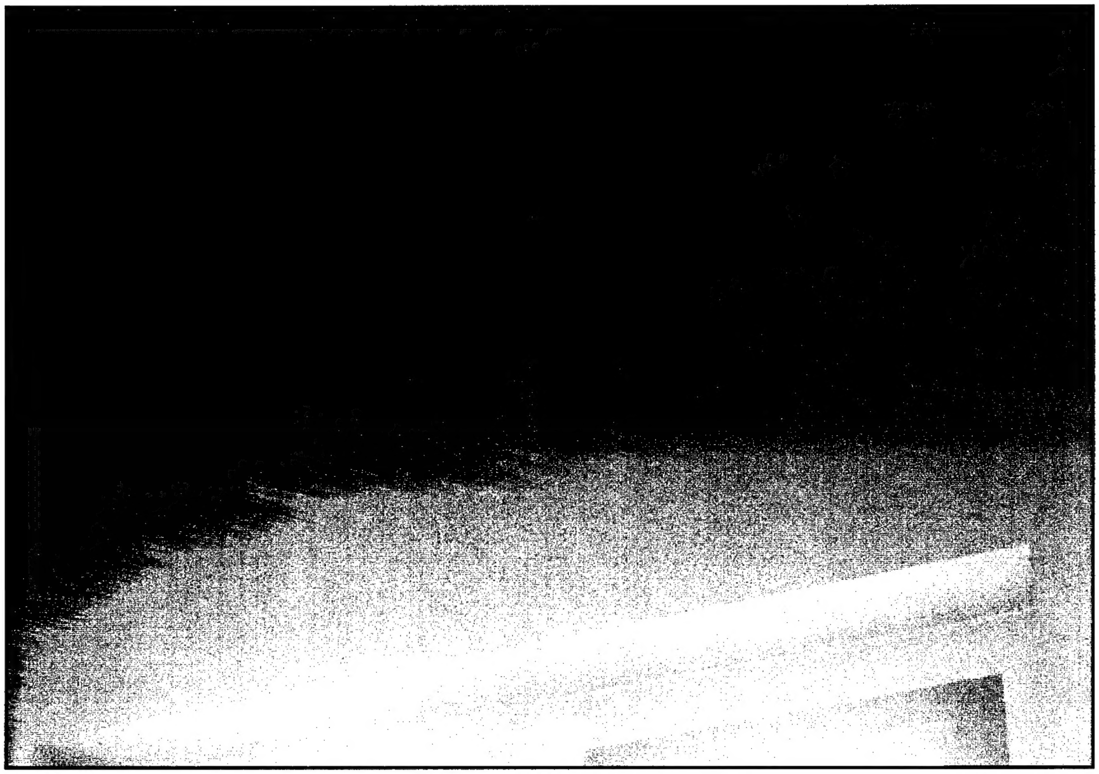


Figure 19. Photograph showing area over window on fifth floor.

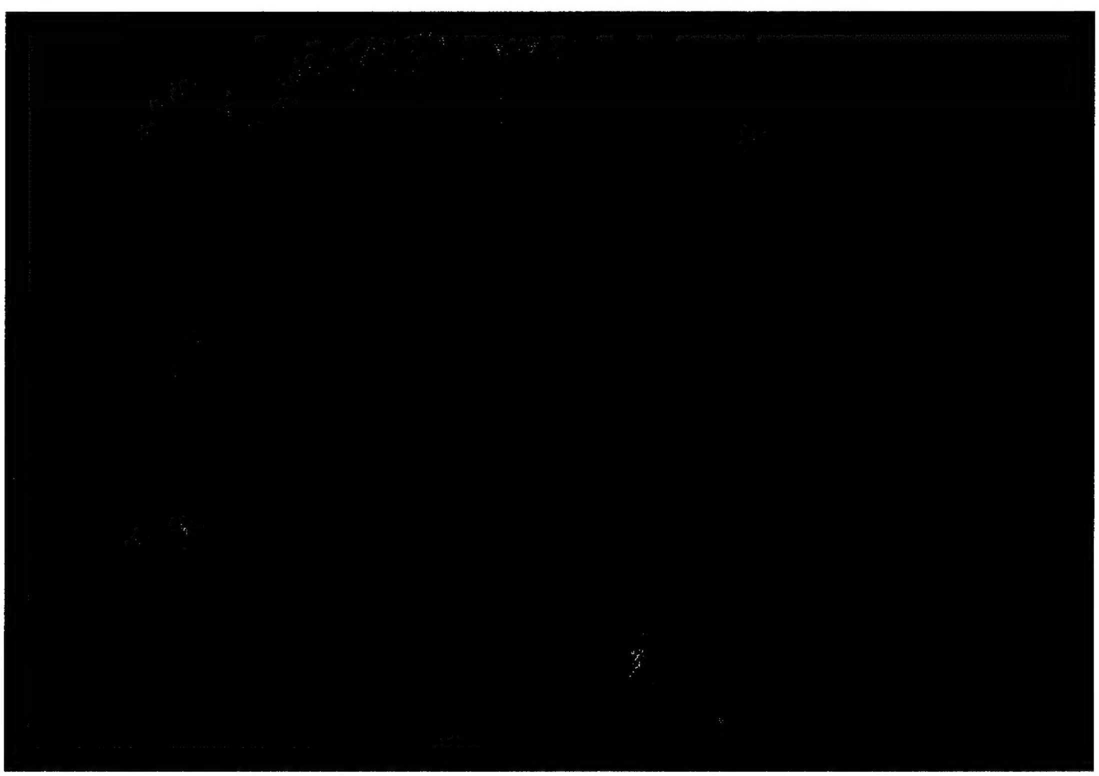


Figure 20. Color-enhanced infrared image of wall showing outline of arch over window.

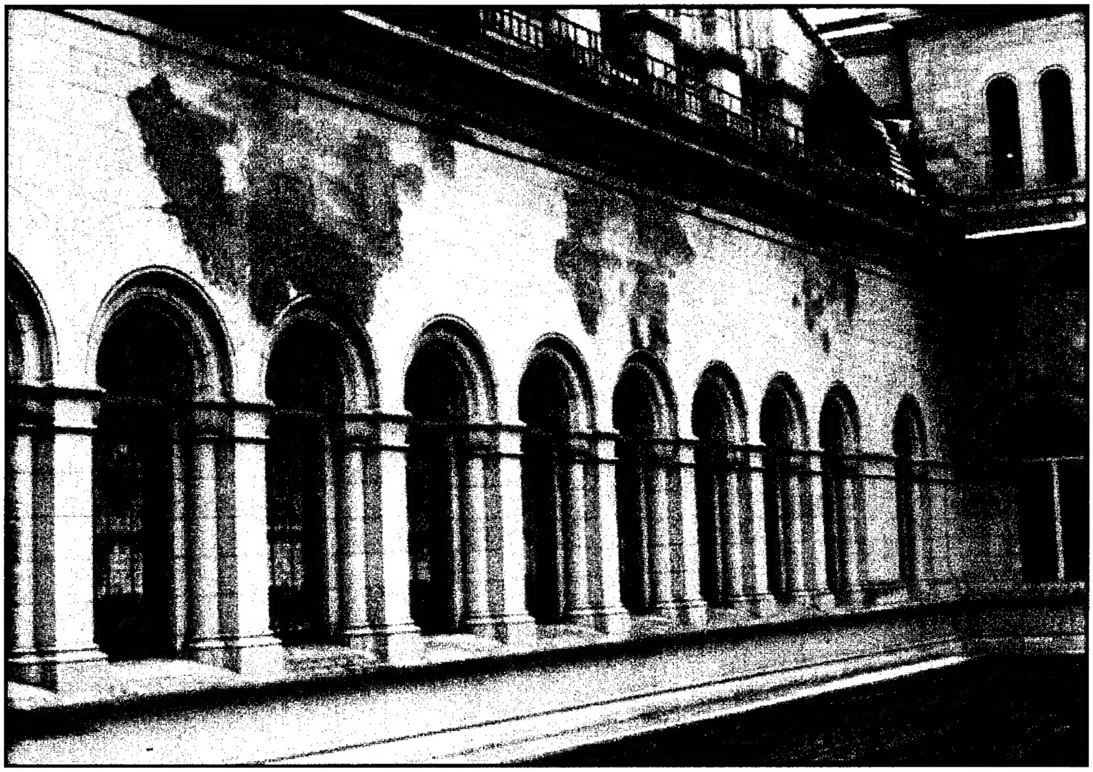


Figure 21. Photograph showing extensive staining of exterior granite wall.

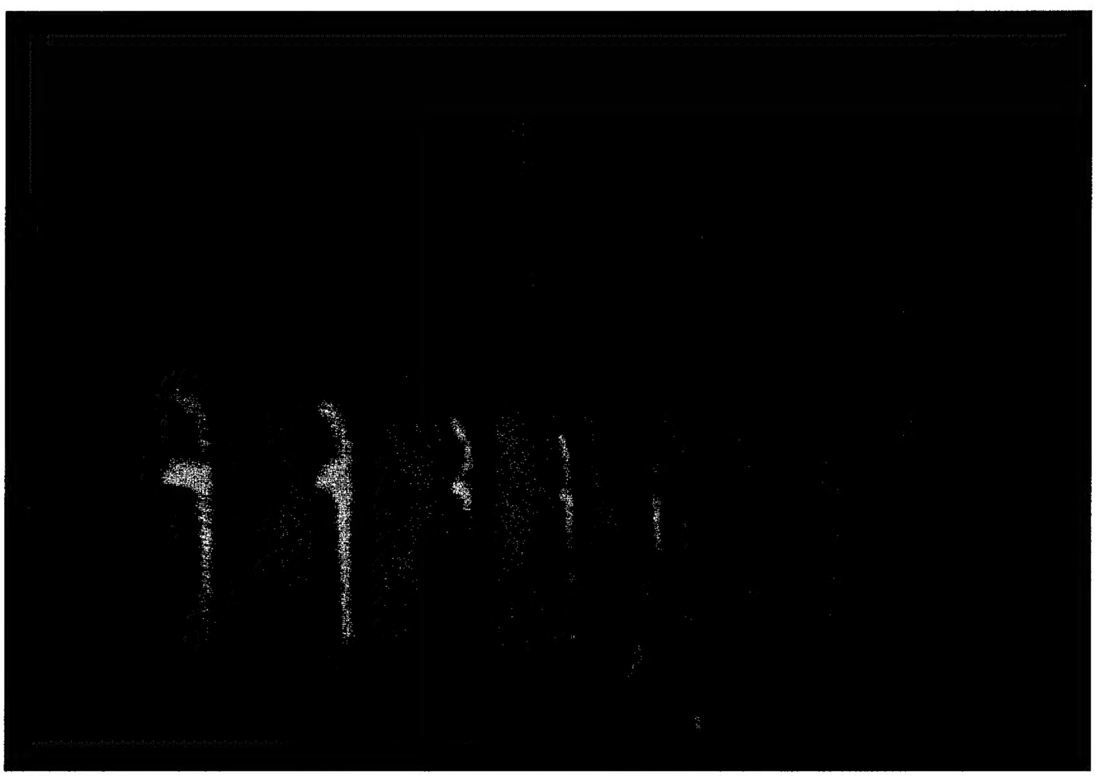
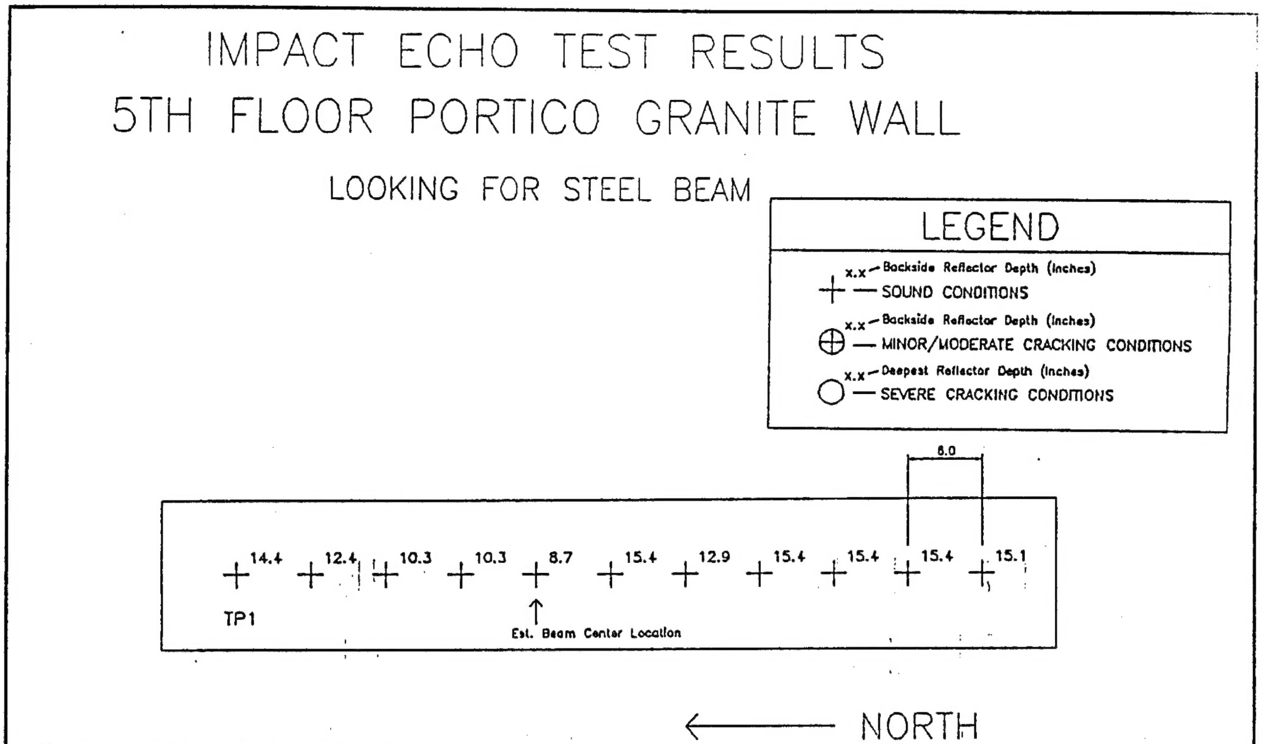
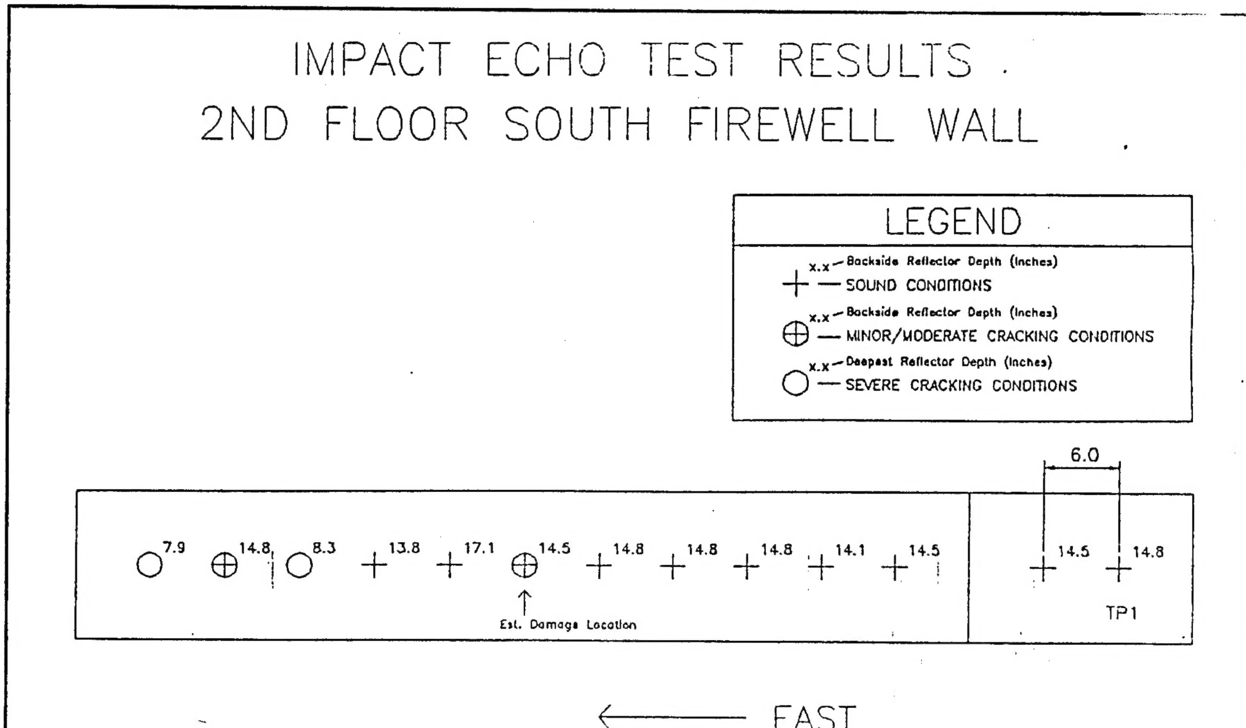


Figure 22. Color-enhanced infrared image of exterior wall showing thermal differential indicating substantial heat loss.



Notes: (1) numbers above the + indicate the depth of cover; (2) IE velocity of 10.3 kips used to calculate all depths; (3) the thinner sections are assumed to be due to the beam rather than severe cracking; (4) the estimated beam location is based on field information.

Figure 23. Metal column in granite/masonry wall with dimensions as determined from impact echo data.



Notes: (1) numbers above the + are depth of cover; (2) IE velocity of 9.4 kips used to calculate all depths; (3) Only the outermost row of granite blocks was tested.

Figure 24. Existing anchors in walls with dimensions as determined from impact echo data.

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